

Ballistic Impact of Dry Woven Fabric Composites: A Review

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This paper reviews the topic of ballistic impact of dry woven fabric composites. It highlights previous work done in modeling the fabrics and the theory involved. Attention is also given to experimental testing, ballistic penetration resistance, projectile characteristics, and failure modes in yarns and fabric. Concepts to further enhance the ballistic penetration resistance of woven fabrics are discussed. This paper serves as an effective source of literature for those interested in conducting research into this topic. Altogether, 176 references have been cited to allow further investigation. [DOI: 10.1115/1.2821711]

Keywords: ballistic impact, woven composite, yarn, fabric, finite element, material model

1 Introduction

The impact resistance of high-strength fabrics makes them desirable in applications such as protective clothing for military and law enforcement personnel, protective layering in turbine fragment containment, armor plating of vehicles, and other similar applications involving protection resistance against a high velocity projectile. Other applications include commercial aircraft and helicopter secondary composite parts, particularly facings of honeycomb sandwich constructions, boat hulls, electrical and electronic parts, and coated fabrics [1]. Farjo and Miclaur [2] reviewed the wounding potential and mechanisms of tissue damage from firearms. This serves to stress the urgent need for protective systems against ballistic threats, especially applicable to body armor. Roberts et al. [3] modeled the effect of nonpenetrating ballistic impact as a means to detect behind-armor blunt trauma (BABT) in humans. A detailed finite element model of the human thorax was developed in LSDYNA with a Kevlar vest modeled over the chest and subject to nonpenetrating ballistic impact. The resulting pressure profiles and kinetic energy of the organs were used to identify mechanisms of injury.

The first high-strength and high-modulus fibers were developed in the 1960s and ushered in a new era of fabric-based body armor that protected against lower-end firearms. Considerable research has been conducted since then, making the fabrics stronger and increasing their ballistic penetration resistance while still maintaining their flexibility. Simultaneously, efforts were on to apply these new armor piercing resistant fabrics to other applications that also needed protection from fragment-simulating projectiles (FSPs).

Depending on the class to which they belong to, different fibers have different structural properties, leading to different responses to ballistic impact when woven into a fabric. Some examples are aramids, such as Kevlar (DuPont) and Twaron (Teijin); poly(phenylene benzobizoxazole) (PBO) fibers, such as Zylon (Toyobo); ultraheavy molecular weight polyethylene (UHMWPE), such as Spectra (Allied Signal); and PIPD fibers, such as M5. Other examples of commercial brands are Vectran (Hoechst Calanese), Technora (Teijin), and Nextel (3M Ceramic Fiber Products). These fibers are characterized by their high stiffness and strength to weight ratios. Individual yarns do not possess the strength to safeguard against ballistic impact; however, when woven together into a fabric, they possess a strength that is much larger than the sum total of the individual strands and also possess a strength to weight ratio higher than steel. This is attributed to the fabric

weave, architecture, yarn crimp, and the various mechanisms of energy absorption of the fabric, discussed later. To briefly compare various commercial brands of fabrics, Zylon woven fabrics absorb nearly twice the energy per unit areal density [specific energy absorbed (SEA)] than both Kevlar and Spectra, when gripped on all four edges, and almost 12 times that of aluminum fuselage skin. The ballistic impact performance of PBO systems is substantially superior to Kevlar 29 systems and marginally better than Kevlar KM2 systems [4]. It is reported in Ref. [5] that Spectra fibers are ten times stronger than steel.

Previous review work includes a database of early ballistic fabric research by Cunniff [6], and the mechanisms influencing ballistic performance of woven fabrics by Cheeseman and Bogetti [7].

2 Modeling the Ballistic Impact of Fabric

Over the past few decades, many different techniques have been used to derive the constitutive relations and model the overall fabric behavior for use in ballistic impact applications. Different models include various effects and phenomena associated with the ballistic impact of fabrics; however, there is no single comprehensive model that reproduces and represents all phenomena at the same time. However, many simplistic models have been found to yield results that are realistic.

2.1 Classification According to Underlying Theory. Researchers adopt different ways to approach the modeling of the ballistic response of dry woven fabrics. The methodology is discussed in later paragraphs. This section simply enlists the approaches adopted by various authors chronologically in each category.

2.1.1 Analytical. Analytical methods make use of general continuum mechanics equations and laws, such as the conservation of energy and momentum. Governing equations are set up using various parameters involved during the impact process. Analytical methods are useful to handle simple physical phenomena, but become increasingly complicated as the phenomena become more complex and involve many variables. This includes work by Vinson and Zukas [8], Taylor and Vinson [9], Parga-Landa and Hernandez-Olivares [10], Hetherington [11], Cox and Flanagan [12], Chocron-Benlouou et al. [13], Navarro [14], Walker [15], Billon and Robinson [16], Gu [17], Phoenix and Porwal [18,19], Xue et al. [20], and Naik et al. [21].

2.1.2 Semiempirical and Empirical. Empirical studies rely on the analysis of data obtained through experimental work in order to examine the fabric response and obtain constitutive relations and failure criterion. This includes curve fitting, nonlinear regres-

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sion analysis of experimental data, and the use of statistical distributions. Parametric equations relate the various parameters studied during the experiment. The method is useful when there are small numbers of variables to correlate [22]. The shortcoming is that the accuracy of the obtained model will depend on the accuracy and completeness of the collected data. This includes work by Cunniff [23], Shim et al. [24], and Gu [25].

2.1.3 Numerical. This approach relies on techniques, such as finite element and finite difference methods, and the use of commercial packages, such as ABAQUS, DYNA3D, and LSDYNA, to conduct the analysis or simulation. Contact between the yarns, fabric plies, and projectile is better handled through the use of commercial software. Further, the fabric yarns may be modeled explicitly, which leads to the capturing of certain phenomena that are not fully possible in other approaches, such as yarn pullout and the effect of interyarn friction. This includes work by Roylance et al. [26], Roylance and Wang [27], Hearle et al. [28], Shim et al. [29], Lomov [30], Johnson et al. [31], Teng et al. [32], Simons et al. [33], Billon and Robinson [16], D'Amato [34,35], Tarfaoui and Akesb [36,37], Lim et al. [38], Tan and co-workers [39,40], Lim et al. [38], Gu and Xu [41], Boisse et al. [42], and Duan et al. [43–45].

2.1.4 Micromechanical. In a micromechanical approach, the fabric geometry is usually represented by a representative volume cell (RVC), which by repeated translation will yield the entire fabric structure. This RVC is then analyzed through conditions of equilibrium of forces or variational potential energy methods to compute displacements, strains, and stresses. This includes work by Dasgupta et al. [46], Vandeuren et al. [47], Tan et al. [48], Sheng and Hoa [49], Tabiei and Ivanov [50,51], and Xue et al. [52].

2.1.5 Multiscale Constitutive. Multiscale approaches make different assumptions of fabric behavior at different scales. This arises due to the inherent multiscale nature of fabrics that are constructed from microscale fibrils. For example, the fabric behaves as a continuum membrane at the macroscale; at the microscale, the behavior is accounted for by constitutive modeling of the yarns as elastic or viscoelastic members. This includes work by Nadler et al. [53] and Zohdi and Powell [54].

2.1.6 Variational. Variational principles include the Reissner variational principle, Galerkin method, Rayleigh–Ritz method, and principal of minimum potential energy. These yield governing differential equations, which can then be numerically solved using finite element and finite difference methods. This includes work by Leech et al. [55], Roy and Shin [56], Sheng and Hoa [49], and Sihn and Roy [57].

2.1.7 Experimental. In order to validate the results from theoretical approaches, experimental data are required. Further, by experimentally studying the ballistic impact of woven fabrics, new mechanisms of energy absorption and failure may become apparent, and the effect of various parameters on the ballistic response can be individually and collectively studied. This includes work by Susich et al. [58], Wilde et al. [59], Prosser [60], Prosser et al. [61], Field and Sun [62], Starratt et al. [63], Cunniff [64], Shockey et al. [65–69], Wang and Xia [70,71], Shim et al. [72], Manchor and Frankenberger [73], Lundin [74], Orphal et al. [75], and Rupert [76]. This is discussed in further detail in later sections.

2.2 Research Based on the Number of Fabric Plies Studied. Majority of the literature available today dealing with ballistic impact of fabrics focuses on experimental and theoretical work of a single fabric layer. The complexity of the analysis increases with the number of fabric layers because of the inclusion of new energy dissipation mechanisms and increased interactions between different plies of the fabric and between the target and projectile. Few literature deals with the ballistic impact of armor composed of multiple identical layers of fabric, such as Vinson

and Zukas [8], Hearle et al. [28], Taylor and Vinson [9], Parga-Landa and Hernandez-Olivares [10], Vandeuren et al. [47], Lomov [30], Chocron-Benloulou et al. [13], Barauskas et al. [77], Navarro [14], Cunniff [4,78,79], Billon and Robinson [16], Sheng and Hoa [49], Tan et al. [39], Lim et al. [40], Zohdi [80], Blankenhorn et al. [81], and Porwal and Phoenix [19]. There is very limited work on ballistic impact of fabrics composed of multiple layers of different fiber materials, such as Hearle and Sultan [82], Cunniff [83], and Porwal and Phoenix [19].

2.3 Commercial Finite Element Software Packages Used for Analysis. With the advent of supercomputing, commercial finite element packages are gaining popularity because of the low cost alternative offered to costly experimentation and destructive testing, as well as the testing of potential materials not yet developed. Finite element packages also offer the option of using of user-defined material models in place of the standard material models and thereby provide a useful platform for the testing of new theories utilizing a numerical form of solution. Finite element codes can also handle complex interactions between the projectile and fabric, penetration, contact and friction between yarns, and the deformation and failure of the fabric. Thus, it is a very useful tool for the simulation of ballistic impact of woven fabrics.

In the ballistic impact testing of fabrics, the most commonly used commercial finite element packages are ABAQUS by ABAQUS Inc., which involves the ABAQUS/STANDARD and ABAQUS/EXPLICIT solvers, DYNA3D, which is part of a set of public domain codes developed in the Methods Development Group at Lawrence Livermore National Laboratory (LLNL) [84], and LS-DYNA by Livermore Software Technology Corporation [85,86].

A few examples of research into ballistic impact of woven fabrics that use these finite element packages are ABAQUS used by Xue et al. [20] and Diehl et al. [87], DYNA3D used by Shockey et al. [65,66] and Lim et al. [38], and LSDYNA used by Tabiei et al. [50,51,88,89], Shockey et al. [67–69], Shahkarami et al. [90], Blankenhorn et al. [81], Gu et al. [17,25], and Duan et al. [43–45,91].

2.4 Computer Software and Codes for Solid Modeling and Computing Properties of Textile Composites. Specialized codes are available that are capable of generating 3D fabric models based on user input of parameters, such as weave density, crimp, and number of layers. These models can then be imported into the preprocessor of a commercial finite element package. Brown et al. [92] described a technique to automatically generate a solid model of the representative volume element (RVE) of the fabric structure. The solid model is generated using a program file written in I-DEAS Open Language. Cox and Flanagan [12] listed various codes used in the computation of textile composite properties, especially macroscopic stiffness, strength, and, occasionally, damage tolerance. These include μ TEX-10 and μ TEX-20 by Marrey et al., TEXCAD by Naik, PW, SAT5, and SAT8 by Raju, SAWC by Whitcomb, CCM-TEX by Pochiraju, WEAVE by Cox, and BINMOD by Cox et al.

2.5 Approaches to Modeling According the Author(s). This section reviews some of the approaches adopted by various researchers that are frequently cited in open literature. It is by no means a comprehensive listing and merely serves to highlight the varied and innovative nature of research into the ballistic impact of woven fabrics.

Vinson and Zukas [8] and Taylor and Vinson [9] modeled the fabric as conical isotropic shells. The model treated the fabric as isotropic and did not differentiate between warp and weft directions, leading to a conical shaped transverse deflection of the fabric, which is contrary to experimental findings. Leech et al. [55] and Hearle et al. [28] modeled the fabric as a net. Prosser [60] derived a mathematical model for the FSP-nylon system in his study of ballistic impact of nylon panels by 0.22 caliber FSPs. He stated that for a set of V_c determinations, plots of V_r (residual) and

V_s (striking) can be adequately represented by parabolas. There are periods in the plots of the squared V_{50} velocities and number of layers, where the plot linearity signifies that the mechanism of penetration is constant. Cunniff [83] examined system effects that occur during the ballistic impact of woven fabrics by developing a conceptual framework that relates ballistic impact mechanics of a single yarn to ballistic impact mechanics of the fabric. Ting et al. [93] extended on the work of Roylance et al. [94] and provided for contact between adjacent plies of a multiply target and introduced slippage at yarn crossover points. Their model predicted an increase in the ballistic limit when the friction of slippage increases. Cunniff and Ting [95] developed a numerical model that treated yarns as elastic rod elements based on the work of Ref. [27]. Walker [15] developed a constitutive model for an anisotropic fabric sheet based on elastic deformations of the fibers. The centerline deflection of the fabric sheet was solved with an approximate analytical solution that yields the final deformed fabric shape and a simple equation for the force-displacement curve. Ting et al. [93] and Shim et al. [29] modeled the fabric material as an orthogonal grid of pin-jointed member elements. Shim et al. [24] used a three-element spring-dashpot model to represent the viscoelastic behavior of the fibers and capture its strain-rate sensitivity. The model accounts for yarn crimp. Roylance et al. [26] modeled the fabric as an orthogonal mesh assembly of nodes interconnected by flexible fiber members. A finite difference method was applied at the yarn crossover points to simulate ballistic impact. Artificial backup springs in the transverse direction play a significant role in the ballistic limit determination. The model lacks contact surfaces to interact with the projectile. Johnson et al. [31] modeled the fabric with both pin-jointed members and thin membrane shells. The computational model used a constitutive strength and fracture model that depended on individual fiber characteristics. The bilinear stress-strain relationship is assumed for the bar members to simulate yarn crimp. Shell elements provide the contact surface and shear stiffness.

Shockey et al. [65–69] used finite solid elements to explicitly model individual yarns and combined them in an orthogonal weave to form the fabric. The model was found to be computationally very expensive and became unstable as the number of elements used to discretize the yarns crossed a certain value. However, the explicit yarn modeling allowed for the observation of phenomena such as yarn-yarn interaction and yarn pullout. Kamiya et al. [96] reviewed recent advances in the fabrication and design of three-dimensional textile performs. Their review detailed advances made toward realizing an integrated approach in the design and manufacture of three-dimensional textile performs. Rao and Farris [97] experimentally and theoretically studied the influence of twist on the mechanical properties of high performance fiber yarns, including Kevlar 29, Kevlar 49, Kevlar 149, Vectran HS, Spectra 900, and Technora. A model based on composite theory was developed to highlight the decrease in modulus as a function of degree of twist and elastic constants of the fibers. They concluded the existence of an optimal twist angle of around 7 deg, where all fibers exhibit their maximum tensile strength. At higher angles of twist, the fibers get damaged, reducing their tensile strength. The study of Gasser et al. [98] aimed at recalling the specificity of the mechanical behavior of dry fabrics and to understand the local phenomena that influence the macroscopic behavior. 3D finite element analysis was compared to biaxial tests on several fabrics. The developed model helped understand the main aspects that lead to the specific behavior of woven fabrics and also helped design new fabrics by varying mechanical and geometric parameters. Billon and Robinson [16] considered the fabric to be a collection of pin-jointed members. Both an analytical method and direct step finite element method were used, and their results were compared to experimental results. The input to the analytical model includes fabric material properties, a constitutive relation and a failure criterion. The model then predicts the ballistic limit and residual velocity. Lim et al. [38] modeled fabric armor com-

posed of Twaron fibers in the finite element code DYN3D, using membrane elements under the continuum assumption of fabric. A standard isotropic strain-rate-dependent elastic-plastic model was used to incorporate the strain-rate dependency of the Twaron fibers studied in Ref. [24]. Since the fabric architecture such as yarn crimp and cross section was not considered, and the material was treated as isotropic, the deformation of the fabric was conical when in fact it should have been pyramidal. Cheeseman and Boggett [7] reviewed the factors that influence ballistic performance, specifically, the material properties of the yarn, fabric structure, projectile geometry and velocity, far field boundary conditions, multiple plies, and friction.

Ivanov and Tabiei [99] considered the fabric to be a grid of pin-jointed bar elements in their micromechanical approach. Tabiei and co-workers [50,51,99–101] modeled the fabric as thin shells and developed their own material model for use with the shell elements, which included effects of fiber reorientation and locking angle, and fabric architecture such as crimp. The trellis mechanism behavior of the flexible fabric in a free state before the packing of the yarns is achieved by discounting the shear moduli of the yarn material. The fibers were treated as viscoelastic members with a strain-rate-based failure. The model was implemented as a user-defined subroutine in LSDYNA. Contact forces at the fiber crossover points were used to determine the rotational friction that dissipated a part of the energy during reorientation. Gu [25] explicitly modeled individual yarns and combined them to form the fabric mesh. A bimodal Weibull distribution was used to form the tensile constitutive equations of the Twaron yarn at high strain rates. Diehl et al. [87] used ABAQUS/STANDARD and ABAQUS/EXPLICIT to model the structural performance of systems containing woven fabrics. They investigated the limitations and numerical problems of classical orthotropic lamina models and introduced an improved generalized cargo-net approach, models for membrane-only and general shell behaviors, and experimental measurements utilized to obtain effective modeling constants and parameters. Termonia [102] formulated the mechanics of wave propagation in terms of impulse-momentum balance equations, which are solved at each fiber crossover using a finite difference technique. The model accounts for projectile characteristics, such as shape, mass, and velocity, and also fiber properties such as denier, modulus, and tensile strength. The model also considers yarn slippage through the clamps, which is often seen in experimental work. Termonia [103] also numerically investigated the puncture resistance of fibrous structures by driving a needle shaped projectile through a single fabric ply at a constant velocity of 100 m/s. Termonia et al. [104] theoretically studied the influence of the molecular weight on the maximum tensile strength of polymer fibers.

Barauskas and Kuprys [105] developed a model that could handle the collision between fabric yarns in woven structures, where the longitudinal elastic properties of each yarn are presented as a system of nonvolumetric springs. Their collision and response algorithm worked in a 3D space and was based on tight fitting of the yarns by using oriented bounding boxes, with a separation axis theorem to handle collision detection between the oriented bounding boxes. They assumed the yarn cross-sectional area to be constant and elliptical in shape, with changing lengths of axes. Their system is characterized by a significant reduction in degrees of freedom while still preserving the volumetric behavior of the structure, when compared to traditional models that consider yarns as fully deformable volumetric bodies. Phoenix and Porwal [18] developed a membrane model based on an analytical approach to study the ballistic response and V_{50} performance of multiply fibrous systems. They developed solution forms for the tensile wave and curved cone wave considering constant projectile velocity, and obtained an approximate solution for the membrane response using matching boundary conditions at the cone wave front. Then, projectile deceleration due to membrane reactive forces was considered to obtain other results, such as cone veloc-

ity, displacement, and strain concentration versus time. A later study by Porwal and Phoenix [19] based on the above membrane model studied the system effects in the ballistic impact of a cylindrical projectile into flexible, multilayered targets with no bonding between the layers. Each layer was assumed to have in-plane, isotropic, and elastic mechanical properties.

3 Experimental Testing of Ballistic Impact of Fabrics and Study of Yarn Mechanical Properties

As mentioned in earlier sections, experimental testing provides an important source of data that can be used to test the validity of theoretical approaches. It provides a wealth of information into the mechanical and material properties of the constituent yarns and fabrics. It also forms the basis for empirical studies.

3.1 Photographic Investigation and Continuous Monitoring Systems. Susich et al. [58] conducted a microscopic study of impact of multilayer nylon body panel armor. Wilde et al. [59] conducted a photographic investigation of high-speed missile impact upon a nylon fabric. An important inference from this study, as observed by Gu [25], is that the initial shape of the deformed fabric target upon impact is pyramidal, and it transforms into a conical shape after the projectile completely penetrates through the fabric target. Prosser et al. [60] used optical sensors in his study of the penetration of nylon panels by FSPs. Starratt et al. [106] designed a simple, cost effective continuous measuring system, called the enhanced laser velocity system (ELVS), to study the ballistic impact of fabric targets. Through simple mathematical operations, the system could be configured to determine the time histories of velocity and acceleration, impact force, and projectile energy loss during an impact. Mitchell and Carr [107] used an environmental scanning electron microscope to examine the post-failure of body armor textiles. Prosser et al. [61] studied the effect of heat on the penetration of cloth ballistic panels. Evaluations by light microscopy, polarized light microscopy, and scanning electron microscopy showed heat induced damage in the fibers along the path of the projectile. Field and Sun [62] conducted a high-speed photographic study of fibers and woven fabrics. Steel balls were fired at velocities up to 1000 m/s into various fibers and Kevlar fabrics, and the transverse wave speeds were examined. They concluded that materials having a high stress wave velocity were advantageous in dissipating more impact energy by involving more yarns and therefore material in the energy dissipation process by propagating stresses and strains more quickly to neighbouring fibers. Field et al. [108] also reviewed experimental techniques used in high rate deformation and shock studies. Shockey et al. [66] used scanning electron microscopy to study fibers, of Zylon, Spectra, and Kevlar that had failed after yarn tensile tests.

Schmidt et al. [109] described how a pair of high-speed digital cameras using 3D image correlation photogrammetry can provide full-field dynamic deformation, and shape and strain information. This technique is used to validate and iterate certain LSDYNA models as well as Kevlar ballistic impact testing, where the aim is to quantify the maximum out-of-plane deflection that occurs at velocities approaching the penetration threshold. Full field behavior such as dynamic rippling, comparison of various weaves, and alternative ballistic fabrics can also be analyzed [109].

3.2 Experimental Work. The work of Shockey and co-workers [65–69,110,111] formed an excellent and extensive source of experimental data into the ballistic impact of woven fabrics, including load stroke, stress-strain, specific energy absorption, and residual velocity data, as well as the effect various parameters have on the ballistic penetration resistance of fabrics. A video camera used in push tests simultaneously records the deforming backsurface of the fabric at a very low angle to show fabric deformation along the plane of the fabric, as well as a mirror that is inclined at 45 deg to the fabric, which allows a 90 deg view or vertical view of the backsurface of the deforming fabric. The camera can be zoomed in to allow a resolution of

individual yarns. A scanning electron microscope was also used to study the cross-section failed yarns. A large number of experimental tests were conducted, which involved tensile testing of yarns, push rod tests of fabric meshes, as well as large scale impact tests with gas guns and aircraft fuselages lined with high energy-absorbing fabrics at the NAWC-China Lake test facility. Further large scale tests including engine debris penetration were conducted by Lundin [74] and Manchor and Frankenberger [73].

Cunniff [64] used a compiled database of experimental V_r and V_s data that included various materials such as nylon, Kevlar, and Spectra; projectile shapes such as steel and tungsten right circular cylinders, steel chisel-nosed FSPs, steel cubes, and steel and tungsten spheres; projectile masses ranging between 2 and 128 grains; and obliquities ranging between 0 deg and 45 deg apart from standard normal obliquities, to establish a generalized relationship for body armor V_{50} and residual velocity as a function of various parameters listed in the database. This was used to estimate V_{50} velocities where no prior data exist, V_s - V_r curves for new materials, and variation of V_{50} velocity with changes in test conditions and procedures. Rupert [76] observed that very few open literature was available for current pistol ammunition protection by fabric systems, which could be used to calibrate specialized numerical and analytical fabric models for other applications. He presented a base line calibration data set for the 9 mm M882 NATO Ball round against 10, 20, and 30 plies of Hexcel Schwebel style 706 Kevlar KM2 fabric. V_{50} values were calculated using the maximum likelihood method [112], and estimates for limit velocity and parameters describing the overmatching case were based on Lambert's V_s - V_r method [113]. Orphal et al. [75] performed ballistic tests against a Zylon fabric to measure the fabric displacement and radius of fabric deformation against time, and analyzed the results in the context of the Walker model [15].

Gu [17] used a MTS material tester and split Hopkinson bar to study the tensile properties of the Twaron filament yarn at strain rates varying from 0.01 s^{-1} to 1000 s^{-1} . Shim et al. [72] experimentally investigated the impact of a Twaron woven fabric by 12 mm diameter spheres at varying impact speeds and angles of incidence. They concluded that at low impact speeds and obliquity, there is a sliding of the projectile along the fabric surface leading to an additional mode of energy dissipation. For higher angles of incidence (30 deg and 45 deg), a postperforation deflection of the projectile is observed, which increases with impact velocity. Yang et al. [114] analyzed stress uniformity in split Hopkinson bar test specimens and provided guidelines to assess the validity of experimental data. A split Hopkinson bar apparatus is frequently used in the experimental determination of fabric mechanical properties. Kinari et al. [115] developed an impact tensile testing apparatus based on the one-dimensional elastic-stress-wave theory. The load induced in the specimen was measured by a cantilever-type load cell. Stress-strain curves for strain rates ranging from 10^{-3} s^{-1} to 10^{+3} s^{-1} were obtained. It was observed that the breaking load and modulus increased consistently with strain rate, while the elongation to failure decreased. Later, Kinari et al. [116] developed a new impact tensile testing apparatus to investigate dynamic mechanical properties of super fiber yarns such as aramid and carbon fibers with smaller breaking elongation than most synthetic fibers. Stress-strain curves for strain rates ranging from 10^{-3} s^{-1} to 10^{+3} s^{-1} were obtained. Cheng et al. [117] experimentally studied the stress-strain behavior of a single Kevlar KM2 fiber, the effect of loading rate, and axial-transverse loading interaction. They concluded that longitudinal tension can stiffen the transverse behavior at large deformations, while large residual strains in the transverse direction do not significantly alter mechanical properties in the longitudinal direction. The mechanical behavior of Kevlar KM2 fibers was also found to be insensitive to loading rates in the range of 1400^{-1} – 2500 s^{-1} .

Wang and Xia [70,71] studied the effect of strain rates varying from 10^{-4} s^{-1} to 10^{+3} s^{-1} and temperature varying from -60°C to 90°C on Kevlar 49 aramid fiber bundles. Stress-strain

curves obtained showed the strain rate and temperature sensitivity of the mechanical properties of Kevlar 49 fibers. They observed the initial elastic modulus, strength, and failure strain increase with increasing strain rate for a constant temperature, and the initial elastic modulus decreases and failure strain increases with increasing test temperature for a fixed strain rate.

The puncture and tearing of woven fabrics was experimentally studied by Primentas [118]. The effect of impact angle and puncture mass on the tear propagation length was studied. Shin et al. [119] developed a test procedure for evaluating the cut resistance of yarns under tension-shear loading conditions. A knife blade is transversely pressed at a constant rate against a gripped Zylon yarn, and the load-deflection response is studied from which the energy required for the cut-through is computed. Prosser [120] studied the impact of nylon ballistic panels by 0.22 caliber FSPs and concluded that the major mode of penetration was by a cutting, shearing action and that the force required for shearing failure of yarns was less than that by tensile failure.

3.3 Estimation of Yarn Elastic Modulus in the Transverse Direction. Hadley et al. [121] determined the transverse Young's modulus through a relation between contact area and compressive force through an analytical solution to this plane strain problem. Pinnock et al. [122] measured change in fiber diameter parallel to the plane of the flats as a function of compressive load. Transverse Young's modulus was then determined using another analytical method. Kawabata [123] derived a relationship between compressive load and displacement measured by a force transducer and linear differential transformer mounted on the push rod to determine the transverse Young's modulus. Cheng and Chen [124] used a theoretical analysis to derive an equation between transverse compressive force and displacement from which transverse Young's modulus can be determined after determining two Poisson's ratios and longitudinal Young's modulus. Cheng et al. [125] reviewed the aforementioned literature and also studied the transverse mechanical properties of Kevlar KM2 fibers and determined the transverse elastic modulus of those fibers to be 1.34 ± 0.35 GPa. They concluded that Kevlar KM2 fibers exhibit a phenomenon similar to the Mullins effect (stress softening) in rubber [124]. The Young's modulus in the longitudinal direction and Poisson's ratios were also determined. Gasser et al. [98] stated that yarn thickness variation during tension is very significant and can reach locally important values between 30% and 40%. Ting et al. [126] studied the effect of transverse yarn interaction and found it had a significant influence on textile ballistic response.

3.4 Friction and Tribological Properties of Yarns and Woven Fabrics. Friction plays an important role in determining ballistic effectiveness of a fabric. There are three sources of friction during the ballistic impact of woven fabrics: yarn-yarn friction, projectile-yarn friction, and fiber-fiber friction. Briscoe and Motamedi [127] studied the role of interfacial friction and lubrication in yarn and fabric mechanics, and later Briscoe and Motamedi [128] examined the role of yarn friction on Kevlar 29 and Kevlar 49 fibers. Kirkwood and co-workers [129,130] studied yarn pullout as a mechanism for dissipating ballistic impact energy in Kevlar KM2 fibers. A semiempirical model was developed to predict yarn pullout force and energy as a function of pullout distance, and included the effect of yarn uncrimping and subsequent translation. The experimental testing was done in a laboratory under quasistatic conditions; however, on comparison with ballistic tests, they concluded that the results of the quasistatic tests could be quantitatively correlated with yarn pullout during ballistic impact. Interyarn friction played a major role in the energy dissipation associated with yarn pullout.

Rebouillat [131] studied the tribological behavior of woven fabrics made from Kevlar yarns of different linear densities and compared it with the behavior of their constitutive yarns with different surface treatments. A traditional friction meter was used for the individual yarns, and a pin-on-disk tribometer [131] was used for

the woven fabric. Relative humidity was observed to affect the friction coefficient for hydrophilic surfaces. The yarn linear-density factor was observed to have the largest impact on friction, with fabrics made of higher linear-density yarns having a lower friction coefficient. The polyvinyl chloride disk used in the tribometer to study the frictional properties as a function of surface treatment yielded good approximations of fabrics sliding on steel [132].

Duan et al. [43–45] used LS-DYNA to numerically study the effect of friction on the ballistic impact behavior of high-strength fabrics. Zeng et al. [133] attempted to include frictional effects into the models proposed by Roylance and Wang [27] and Shim et al. [29]. They concluded that the ballistic response of a woven fabric is very sensitive to the yarn friction for low frictional coefficients, but insensitive beyond a certain level. Their results also showed that high interyarn friction can lead to premature yarn rupture, thus reducing the energy absorption capability of the fabric.

3.5 Effect of Heat Generation During Impact. The primary cause of heat generation during impact is friction between the contact surfaces of the projectile, yarns, and individual filaments. Carr [134] noted fiber melting and the formation of shear bands during the high impact energy studies of UHMWPE yarns. Fiber melting, polymer bridging, and fiber fusion due to heat generation have also been noted by Prosser et al. [61] and Prevorsek et al. [135]. In the absence of substantial twist, yarn extension during pyramid formation results in a temperature rise of 2–3 °C experimentally. During the mechanical compression of Spectra, Kevlar, and nylon panels, the maximum temperature rise was 6.1 °C for nylon. However, temperatures as high as 76.6 °C were recorded on the rear surface of nylon ballistic panels after perforation by a 0.22 caliber projectile [61]. Prosser et al. [61] presented a qualitative analysis to explain the phenomena and concluded frictional heat to be an additional heat sink, resulting in heat induced polymer bridging and crystallinity changes in UHMWPE yarns. Using a finite element analysis, Prevorsek et al. [135] determined that the heat generation and corresponding temperature rise has a minimal influence on the ballistic performance of UHMWPE due to the short time frame in which it occurs.

4 Factors Affecting Mechanical Properties of Fiber Yarns and Ballistic Penetration Resistance of Fabric Meshes

Cheeseman and Bogetti [7] reviewed the mechanisms influencing the ballistic performance of woven fabrics. The ballistic penetration resistance and mechanisms involved are a combination of many simultaneous factors. It is therefore not possible to single out any one factor as the controlling parameter in ballistic impact or to investigate the role of an individual parameter without first explicitly stating the combination of other parameters used in the study. This is confirmed by Prosser et al. [61], stating that if ballistic performance was based solely on yarn toughness, then nylon would have a better ballistic resistance than Kevlar, which as we know is not the case. Laible [136] reconfirmed this by stating that when high-strength polypropylene was compared to nylon having two-thirds the strength, it was found that nylon was the better performer. Roylance et al. [94] summed this up in his observation that the response of fabrics cannot be determined from the properties of the fibers alone since the material properties and fabric geometry combine to produce the structural response. Ballistic performance parameters include ballistic limit, critical and V_{50} velocity, SEA, casualty reduction analysis [137–141], and proof velocity.

Bourget and Pageau [142] introduced a new approach that utilized V_r - V_s experimental data from different material and projectile combinations. This effective velocity (V_{eff}) method aimed at defining a single ballistic performance parameter that represented average energy absorption capability of soft armor materials.

Cunniff [143] derived a dimensionless fiber property U^* defined as the product of the specific fiber toughness and strain wave velocity, which could be used to qualitatively assess the performance of fibers,

$$U^* = \frac{\sigma \varepsilon}{2\rho} \sqrt{\frac{E}{\rho}} \quad (1)$$

He obtained two dimensionless parameters that related ballistic impact performance to fiber mechanical properties independent of impacting projectile mass, presented area, or armor system areal density.

4.1 Yarn Material and Mechanical Properties. According to the theory proposed by Smith et al. [144], the speed at which the longitudinal stress wave propagates through a yarn is given by

$$c = \sqrt{\frac{E}{\rho}} \quad (2)$$

where c is the stress wave speed, and E and ρ are the Young's modulus and density of the yarn material. The longitudinal wave velocity in a warp or weft yarn in a plain-woven fabric is $c/\sqrt{2}$ since the linear density of the yarn along which the wave propagates is effectively doubled in a plain-woven fabric. The higher the modulus of elasticity and the lower the density, the faster the stress wave will propagate through the yarns, and the corresponding fabric through the yarn crossover points. This means that more number of yarns will be involved in the energy absorption process, leading to increased energy dissipation as the stresses and strains are quickly transmitted to adjacent yarns [27]. This was observed in a photographic study by Field and Sun [62]. Roylance [145] stated that the strain wave profile when propagating in a fabric differs considerably from that when propagating in a single yarn upon impact. Termonia et al. [104] studied the influence of molecular weight on the maximum tensile strength of polymer fibers.

The mechanical properties of fibers are highly rate dependent. There is only limited work that has been conducted to determine the rate-sensitive properties of Kevlar yarns [10,66,70,71], Twaron fibers [146], Spectra yarns [66], Zylon yarns [65,66], and fabrics [24]. Wortmann and Schulz [147] examined the nonlinear viscoelastic performance of Nomex, Kevlar, and polypropylene fibers in a single step relaxation test.

4.2 Fabric Architecture. Apart from the high-modulus and high-strength properties of the constituent yarns, the architecture is what gives a fabric its unique ballistic penetration resistance.

4.2.1 Weave and Weave Density. Weave patterns used in ballistic applications are usually plain and basket weaves. It was observed that loosely woven fabrics and fabrics with unbalanced weaves resulted in an inferior ballistic performance [83]. Weave density refers to the number of yarns per unit dimension along the principal yarn directions, with the length dimension usually expressed in inches. For example, 34×34 refers to 34 yarns/in. in the warp and weft directions, respectively. In the studies of impact of single-ply Zylon fabrics by Shockey et al. [67], it was observed that energy absorbed was roughly proportional to the fabric areal density. Ballistic effectiveness did not appear to be a strong function of mesh density or weave tightness as the SEAs of 30×30 , 40×40 , and 45×45 targets were about the same [67]. The density of the weave is also termed as the cover factor and is determined by the width and pitch of the warp and weft yarns. According to Chirtangad [148], the cover factor must lie between 0.6 and 0.95 when used in ballistic applications. Cover factors greater than 0.95 imply yarn degradation by the weaving process, and those lesser than 0.6 imply that the fabric is too loose. The presence or absence of slack does not significantly alter the ballistic penetration resistance [68]. Freeston and Claus [149] observed

that strain wave transmissions and reflections at yarn crossovers do not significantly affect the propagation of the strain wave away from the impact zone.

4.2.2 Twist. There is an optimal twist angle of around 7 deg where all fibers exhibit their maximum tensile strength. At higher angles of twist, the fibers get damaged, reducing their tensile strength [97]. Pan et al. [150] studied the obliquity effect of yarn and observed the effect of different loading angles on the strengths and breaking strains of the yarn specimens using a special technique for tensile yarn sample specimens.

4.2.3 Crimp. Yarn crimp refers to yarn undulation and is a property by virtue of the yarn weave. In a plain weave, the degree of crimp is unbalanced as the warp yarns are usually more crimped than the weft yarns by virtue of the mechanism of the weave formation, where adjacent warp yarns are alternatively raised and lowered with respect to the fabric plane and then weft yarns are led back and forth in a straight direction through these warp yarns and along the fabric plane by the weaving machine. Finally, the raised and lowered warp yarns are brought back to the plane of the fabric to form the final weave. This results in the weft yarns being straighter than the undulated warp yarns. Chitrangad [148] proposed using weft yarns that had a larger elongation to break than the warp yarns, so that both warp and weft yarns would fail at the same moment, reducing the effect of yarn crimp. The resulting hybridized weave was found to have a higher V_{50} velocity than weaves composed entirely of an identical yarn material [148]. Tan et al. [151] compared two methods of modeling crimp with results obtained from experiments. They concluded that accounting for crimp by modeling linear elements in a zigzag manner yielded more accurate results than trying to account for crimp in the constitutive relations.

4.2.4 Number of Fabric Plies. Shockey et al. [67] observed that the SEA was significantly higher for multiply targets than single-ply targets. This was attributed to the fact that interply frictional forces inhibited the sideways motion of the yarns in the first-hit ply, causing an increased ballistic penetration resistance. Lim et al. [40] reported that at high impact velocities, plied double-ply systems perform better than spaced systems for sharp-nosed projectiles, and the reverse is true for hemispherical-nosed projectiles while no distinction can be made for flat-nosed projectiles. Cunniff [83] observed that spaced single plies absorbed more energy than layered systems in his studies of impact of Kevlar, Spectra, and nylon panels with chisel-pointed FSPs. The influence of projectile geometry becomes less significant as the number of plies increases [40,61,152]. Cunniff [78] also observed that armor system response appears to be decoupled through the thickness of a system and is primarily inelastic at high impact velocities relative to the V_{50} velocity. He concluded that some of the relatively expensive armor material at the impact face of an armor system may be replaced by less expensive materials without loss in performance.

Porwal and Phoenix [19] made the following observations from their study. The V_{50} velocity of a target degrades progressively as the spacing between layers is increased relative to the sum of layer thickness without spacing. For a given set of layers with differing mechanical properties, the V_{50} and residual velocity depend on the order of placement. For a system with identical layers of a given in-plane tensile strength, the V_{50} velocity increases with increasing strain-to-failure ratio of the layers.

4.3 Friction. Frictional processes within the fabric systems are important for both normal indentations and ballistic deformations as they control the effective stiffness of the material. Fabrics with high friction and the lowest effective moduli were observed to dissipate larger amounts of energy relative to fabrics with lower friction, for both quasistatic and ballistic deformation processes

[128]. Interyarn friction will also determine the energy required to pull a yarn out of the fabric mesh, which is a significant source of energy dissipation during the failure mode of yarn pullout [129,130].

Duan et al. [91] concluded that friction has an indirect effect on fabric energy absorption by influencing the number of yarns that become involved. They also concluded that yarn-yarn friction hinders relative motion between yarns and resists uncrimping of the fabric weave tightness, inducing the fabric to fail earlier during impact. The projectile-fabric friction delays yarn breakage by distributing the maximum stress along the periphery of the projectile-fabric contact zone, and this substantially increases the fabric energy absorption during later stages of the impact [44]. Interyarn friction is also a source of energy dissipation in multiply systems and needs to be accounted for.

4.4 Target Radius and Gripping Conditions. A longer yarn absorbs more deformational energy prior to failure than a shorter yarn. However, the strain-to-failure ratio for a shorter yarn is greater than that for a longer yarn [66]. The bigger the target fabric area is, the more will be the energy absorbed, provided other parameters remain the same and the impact velocity is below the critical velocity. When the impact velocity exceeds the critical velocity, only a small area in and around the impact zone is responsible for energy absorption and, correspondingly, all the strain is concentrated in that region. Thus, the size of the target fabric area will not influence the energy dissipation in high velocity impacts.

The target boundary conditions play a significant role in ballistic effectiveness. There is very little literature that actually studies the role of target boundary conditions. Shockey et al. [67] observed that fabric gripped on two edges absorbs significantly more energy than identical fabric gripped on four edges. The amount was about 25%–60% more for Zylon and almost double for Spectra. This was attributed to the transferring of load from impacted to adjacent nonimpacted yarns and the triggering of remote yarn failure, which is a higher energy-absorbing mode of failure. Fabric gripped on four corners was found to absorb the most energy of all gripping conditions. In addition to remote yarn failure, an additional mode of failure, corner-hole failure, was observed for fabric gripped on four corners [67]. However, the rate at which the impact velocity of the FSP is reduced will vary according to the boundary conditions, especially initially and then after the first modes of failure occur.

Zeng et al. [153] observed that for fabric gripped on four edges, greater energy was absorbed when the yarns were oriented at 45 deg to the edges than when the yarns were parallel to the edges, as the entire fabric was involved in the energy dissipation. Shin et al. [119] observed that yarn pretension in a fabric serves to induce failure at an earlier instance and also reduce the cut energy of the fabric.

4.5 Temperature. The initial elastic modulus, strength, and failure strain increases with increasing strain rate for a constant temperature, and the initial elastic modulus decreases and failure strain increases with increasing test temperature for a fixed strain rate [71]. There was a 5% observed decrease in the ballistic performance of UHMWPE panels shot in heated ovens when the panels were heated to 110°C [154,155]. Since fabrics are also used in supersonic jet engine fan containment systems, their ballistic performance must also be studied at elevated temperatures. Pereira et al. [156] studied the ballistic impact fabrics composed of PBO and Kevlar 29 fibers at elevated temperatures. They found that PBO absorbed significantly more energy than Kevlar at both room and elevated temperatures. However, after aging at temperatures of 204°C (400°F), PBO lost almost all of its energy-absorbing capability, making it unsuitable for elevated temperature applications.

5 Effect of the Projectile Characteristics

5.1 Projectile Geometry and Mass. Larger FSPs have a larger presented area of impact and, consequently, will have to break more number of yarns to penetrate the fabric [66]. Sharper FSPs more easily penetrate fabric targets, resulting in smaller SEAs than blunt-faced FSPs. Shockey et al. [67] used ungripped woven fabric or felt overlays in an effort to improve ballistic performance against sharp-edged impactors. They observed that the overlay wrapped itself around the impactor during penetration, which resulted in a higher SEA as the wrapped impactor presented a larger impact area.

High impact velocity sharp-edged projectiles can penetrate fabric targets by shearing yarns across their thickness [40,61,83,157]. According to Lim et al. [40], the V_{50} velocity for Twaron CT716 double-ply fabrics decreases in the following order of projectile shape: hemispherical, flat, ogival, and conical. Tan et al. [39] observed in their study of plain weave single-ply Twaron CT716 fabric that conical and ogival projectiles perforated the fabric with the least amount of pullout, flat-headed projectiles sheared through the yarn thickness, and hemispherical projectiles produced the most yarn pullout. The force required for nylon or Kevlar yarn failure is lesser for a rectangular leading surface than for a chisel-shaped leading surface [120].

Shahkarami et al. [90] numerically investigated the effect of projectile mass on energy absorption and identified three distinct regions in the plot of energy absorbed by a fabric versus striking velocity. Zone I corresponded to the subcritical region where the projectile was completely arrested by the target. Zone II is characterized by global deformation and strain energy buildup preceding the deformation. In Zone III, the projectile loses a very small portion of its incident energy, and failure is highly localized to the yarns at the impact area [90].

5.2 Impact Velocity and Strain Rate. At lower impact velocities of fabric targets, yarn failure occurs preferentially as intermolecular slippage or secondary bond failure [158], also called failure due to shear. Also, fabric failure due to yarn pullout becomes more predominant. At low impact velocities, the transverse deflection of the fabric has time to propagate to boundaries of the fabric, thereby involving more fabric area in the energy absorption, leading to increased energy dissipation. Low velocity impacts are characterized by excessive creasing and stretching. Stress-strain curves obtained in Refs. [70,71] showed the strain rate sensitivity of the mechanical properties of Kevlar 49 fibers. They observed that the initial elastic modulus, strength, and failure strain increase with increasing strain rate. At high impact velocities of fabric targets, yarn failure occurs preferentially through primary bond failure as the yarns stiffen according to their viscoelastic behavior. Damage becomes localized to the immediate area around the point of impact, and the transverse deflection of the fabric is minimal. Carr [134] observed that during impact of single Kevlar and UHMWPE yarn at high velocities, the yarn failed in shear.

5.3 Projectile Impact Trajectory. The projectile impact trajectory involves the angle at which the projectile strikes the plane of the fabric target and the motion characteristics, such as roll, yaw, and pitch of the projectile. Most studies do not incorporate these projectile parameters into the analysis and consider standard cases of 90 deg angle of projectile impact, with impact velocity or initial projectile kinetic energy as the only projectile-parameter input to the analysis.

5.3.1 Angle of Incidence. At low impact speed and obliquity, there is a sliding of the projectile along the fabric surface, leading to an additional mode of energy dissipation [72], due to friction between the projectile and fabric and possible entanglement of the projectile with pulled out yarns., which in turn dissipates energy as yarn pullout has to overcome warp yarn-weft yarn friction. For higher angles of incidence (30 deg and 45 deg), a postperforation

deflection of the projectile is observed, which increases with impact velocity [72]. For 90 deg or head-on impact, the frictional effect is limited to the projectile's peripheral area in contact with the fabric through thickness, and there is no sliding of the projectile along the surface. In the studies of nylon and Kevlar KM2 based armor systems, Cunniff [79] observed that the V_{50} velocity is a monotonically increasing function of impact obliquity at higher areal densities, accompanied by projectile tumbling during penetration.

5.3.2 Roll/Yaw/Pitch of the Projectile. The roll angle is defined as the angle between the warp yarn direction and the longest dimension of the fragment's impact end or blade direction. At a 45 deg roll angle with respect to the yarn orientation, for example, the impact end of a fragment will intersect and need to break approximately 50% more yarns than at 0 deg to achieve penetration. In the penetration of a Zylon target gripped on two edges, approximately 80% more energy was absorbed for the 45 deg roll angle than for the 0 deg roll angle [67]. At a 45 deg pitch or yaw angle, a fragment presents more of a cross-sectional area to a fabric than at a 0 deg pitch or yaw but may deflect some of these yarns sideways, rather than break all of them, to achieve penetration. Also, the target, particularly a multiple-ply target, may rotate the fragment during penetration, decreasing the hole size and reducing the number of broken yarns on successive target plies [65].

5.3.3 Point of Impact. When the projectile strikes the target fabric at the point of intersection of a warp and a weft yarn, the resistive force offered is greater than when the projectile strikes at the gap formed between two adjacent parallel warp and weft yarns. In the latter case, if the presented impact area of the projectile is small enough, the projectile will try to push the yarns aside and wedge through, resulting in decreased energy absorption by the yarns.

6 Constitutive Modeling of Yarn

The fibers used in the ballistic impact resistant fabrics are viscoelastic. During their constitutive modeling, it is important to account for their strain-rate sensitivity. Properties such as the elastic modulus are dynamic and vary nonlinearly with strain. If static values are used during the analysis of the ballistic impact of fabrics, it will lead to certain inconsistencies between numerical and experimental results, as was observed in Ref. [27]. However, acceptable results are still obtainable by simplifying the behavior of yarns as elastic members.

6.1 Basis of the Three-Element Spring-Dashpot Model. Lim et al. [38] and Ivanov and Tabiei [99] used a three-element spring-dashpot model to represent the viscoelastic behavior of the Twaron fibers. Twaron fibers are very similar to Kevlar fibers as both belong to the Aramid family and have identical static properties.

The viscoelasticity exists as a property of all materials, but it is significant at room temperature for polymeric materials mainly. The creep and the stress relaxation are the results of the viscoelastic behavior of materials. For impact simulations, we do not need the long-term effects of the viscoelasticity, so that the material behavior can be simply described by a combination of one Maxwell element without the dashpot and one Kelvin-Voigt element. The differential equation of viscoelasticity can be derived from the model equilibrium in the form

$$(K_a + K_b)\sigma + \mu_b \dot{\sigma} = K_a K_b \varepsilon + \mu_b K_a \dot{\varepsilon} \quad (3)$$

where σ , ε , and $\dot{\varepsilon}$ are the stress, strain, and strain rate, respectively. Constants K_a , K_b , and μ_b can be derived experimentally and vary according to the material.

The principal behind the response of the fibers at different strain rates is as follows. At low strain rate, below the transition strain rate, the dashpot offers little resistance as damping is proportional to the velocity. The dashpot and parallel connected

spring are free to move according to spring stiffness K_b . Since $K_a > K_b$, spring A remains rigid and spring B displaces preferentially. However, at higher strain rates, above the transition strain rate, the dashpot offers a resistance higher than the stiffness of spring A. Now, spring A moves preferentially compared to the dashpot-spring B assembly, which remains rigid. In reality, spring A represents the primary or intramolecular covalent bonds of the fiber microstructure, while spring B represents the secondary bonds, which are the van der Waal forces and hydrogen bonds. The failure associated with these bonds is discussed in later sections. The transition strain rate for Twaron CT716 was experimentally observed by Ref. [38] to be 410 s^{-1} . Based on their numerical modeling, Ivanov and Tabiei [99] observed the transition strain rate of 840 denier Kevlar 129 to be 100 s^{-1} .

6.2 Basis of the Weibull Distribution. Gu used a Weibull distribution of yarn strength to describe the stress-strain response of Twaron fibers based on Refs. [159,160]. He used a two modal Weibull distribution using the observation form [161] that aramids have a distinct skin-core structure and that defects in the skin and core are the two main factors that influence the yarn strength composed of filaments without twist. From this, Gu obtained the following constitutive relation:

$$\sigma = E\varepsilon \exp \left[- \left(\frac{E\varepsilon}{\sigma_{01}} \right)^{m1} - \left(\frac{E\varepsilon}{\sigma_{02}} \right)^{m2} \right] \quad (4)$$

The scale (m) and shape (σ) parameters were calculated from tensile experimental data of yarn filaments [17] with the Levenberg-Marquardt nonlinear least squares estimation method [162]. Different constitutive relations were obtained based on the strain rate. Wang and Xia [70,71] also used a bimodal Weibull statistical distribution model to describe the strain-rate dependence of Kevlar 49 aramid fiber bundles for strain rates varying from 10^{-4} s^{-1} to 10^3 s^{-1} .

7 Failure Modes in Yarns and Fabric

Failure modes in the filaments, yarns, and fabric can be observed at both the microscopic and the macroscopic level. The microscopic level involves failure through the breakage of bonds that comprise the structure of the filaments, while at the macroscopic level, failure can be observed through mechanisms such as yarn pullout and bowing.

7.1 Breakage of Bonds. Shim et al. [24] described the breakage of bonds that occurs in PPTA fibers, such as Twaron. According to the kinetic theory of fracture [163], bond breakage occurs when it is excited beyond its activation energy. When the activation energy or stress for a particular fracture mode is reached, the fracture mechanism is triggered. At room temperature, which is above the glass transition temperature (T_g) for PPTA and most polymers, the activation stress for shear yielding and intermolecular slip (σ_y) becomes lower than the activation stress for brittle fracture (σ_f); hence, polymers would be expected to fail via shear yielding at room temperature [24]. However, Termonia et al. [158] and Termonia and Smith [163] observed the strong dependence of failure on the strain rate. At low strain rates (about 0.01 s^{-1}), plastic deformation and intermolecular slippage involving the rupture of secondary bonds occur in preference to primary bond breakage. At higher strain rates (about 1 s^{-1}), both primary and secondary bond breakages occur. Following this trend, Shim et al. [24] postulated that at much higher strain rates (about 400 s^{-1}), primary bond breakage or brittle fracture will predominantly occur. This was concluded based on the findings of Termonia and Smith [163], who noted that the higher the strain rate, the shorter the time interval a loaded bond spends at a particular stress level.

7.2 Local Yarn Rupture. Local yarn rupture occurs when all of a yarn's fibers break apart at the same location, usually at the sharpest point of contact between the penetrator and the yarn. A

popping sound accompanies this failure along with a sudden drop in the measured load [67]. The two causes of yarn rupture are the stretching of yarns along their length and shearing across the thickness [40]. The fibers in the yarn will fail when the induced strain crosses the failure strain. The failure strain is rate dependent and generally decreases with increase in strain rate. Simons et al. [164] described a method for modeling damage in finite element calculations during the ballistic impact of high strength fabrics. They assumed that the fibers were elastic until breakage and that fibers break at a uniform rate in the strain range studied. Based on dynamic stress-strain curves of Twaron CT716, Shim et al. [29] identified two response regimes for the variation of failure strain with strain rate.

7.3 Remote Yarn Failure. Remote yarn failure is when the fibers within the yarn break at different points along the yarn's length and not necessarily at the point of impact. The break can occur anywhere between the impact point and the gripping boundaries. The acoustic emission is also less distinct and is usually a softer hissing or rustling sound. During remote yarn failure, the load on the penetrator will be maintained until the frictional forces on the yarns fall below the required values sustain the remote failure [67].

7.4 Yarn Pullout. Yarn pullout occurs when none of the fibers in a yarn break, but one end of the yarn is pulled out of the fabric mesh. This type of failure can only happen with ungripped or loosely gripped yarns. The force required to pull a yarn out of the mesh is the frictional force on the contact area between the yarn and all the intersecting perpendicular yarns. As the yarn is pulled out, the number of intersecting yarns decreases steadily, resulting in a gradual drop in the measured load [67]. Kirkwood and co-workers [129,130] studied yarn pullout as a mechanism for dissipating ballistic impact energy in Kevlar KM2 fibers. The two main mechanisms associated with yarn pullout are yarn uncrimping and subsequent yarn translation. The pullout force was found to be dependent on interyarn friction and yarn pretension. The yarn uncrimping energy is defined as the integral of the force-displacement curve from the starting configuration to the peak load point, and the yarn translation energy is defined as the integral of the force-displacement curve past the peak load point. The sum of the above two energies represents the total energy during pullout [129]. Chitrangad [165] observed that aramid filaments maintained under tension improved the ballistic performance. Energy dissipation due to yarn pullout becomes a very significant factor in low velocity impact of smaller target radii with ungripped yarns.

7.5 Fibrillation. The splitting of fibers along their lengths or fibrillation is a damage mode favored by abrasive action across the fiber length. In multiply systems, fabric-fabric friction results in abrasion perpendicular to the fiber axis. All projectiles that possess capabilities of wedging through the fabric such as hemispherical, ogival, and conical shapes cause a splitting of the fibers that show no significant apparent differences from single-ply systems [40]. Martinez et al. [157] stated that plucking or shagging is involved during a fabric-fabric abrasion and the severity depends on contact pressure between the plies.

7.6 Bowing. The misalignment of orthogonal yarns is also referred to as bowing. Lim et al. [40] observed that bowing is more predominant in the back plies of a multiply system, where the projectile tries to penetrate through a wedge-through approach after having been considerably slowed down by the initial plies. This wedge-through phenomenon has been observed by many researchers, including Montgomery et al. [152], Kirkland et al. [155], Shim et al. [29], Prosser et al. [61], and Lee et al. [166].

The existence of the wedge-through phenomenon is apparent from the size of the hole formed in the fabric being smaller than the diameter of the projectile and a fewer number of yarns being broken than the number of yarns that intersect the projectile [7].

8 Concepts to Further Enhance the Ballistic Penetration Resistance of Woven Fabrics

Researchers are constantly looking toward the development of new materials that have higher strength-to-weight ratio and superior ballistic penetration resistance than the currently available commercial materials, such as Kevlar, Zylon, and Twaron. Efforts are also on to increase the strength of fabrics manufactured with available materials through new concepts and ideas. One popular concept is the coating of yarns with certain chemicals that favorably alter the frictional and tribological behavior of the yarn. Dischler et al. [167] coated fibers with a dry powder that exhibited dilatant properties. The fabric exhibited a superior distribution of ballistic energy compared to fibers that were not coated with this powder. It was attributed to the increase in interfiber friction. Dischler [168] also developed a coating $\sim 2 \mu\text{m}$ thick, which, when applied to aramid fibers, increases yarn-yarn frictional coefficients. Chitrangad et al. [169] developed a fluorinated finish for aramids that increased the fiber-fiber friction as compared to the standard finish used in aramid processing. Rebouillat [170] stated that a processing finish was still required before coating aramids with a fluorocontaining finish, which served as a water repellent agent [7]. This is supported by the studies of Bazhenov [171], who investigated the effect of water on the ballistic performance of a rectangular laminate composed of 20 layers of Armos fabric. He noted that water served as a lubricant that decreased friction between the bullet and yarn and allowed the bullet to slip through the fabric by moving yarns laterally.

Lee et al. [172,173] studied the ballistic impact characteristics of Kevlar woven fabrics impregnated with a colloidal shear thickening fluid. They reported an increase in the ballistic penetration resistance without the loss in flexibility of the impregnated Kevlar fabric. At low strain rates, colloidal shear thickening fluids do not offer much resistance to fabric deformation or bending; however, at higher strain rates, the fluid thickens, resulting in increased resistance to ballistic perforation [172]. Sickinger and Herrmann [174] described structural stitching as a method to develop high performance composites in the future. Chitrangad [175] used a combination of woven para-aramid fiber sheets and compressed pulp sheets in the construction of a ballistic protection agent. The construction improved wearer comfort and flexibility while providing the same level of ballistic protection.

Researchers are also looking toward using deflector plates in fabric systems that would initially slow down projectiles by deflecting them sideways and twisting them, and in certain cases even causing their leading edge to become blunt upon impact. Carbon nanotubes possess exceptional mechanical properties, such as strength, stiffness, and resilience coupled with low density [176]. With the advent of nanotechnology, the inclusion of carbon nanotubes (fullerene molecules) with the fabric material is being investigated to drastically increase the strength and ballistic penetration resistance of the fabric.

9 Concluding Remarks

This paper has reviewed the topic of ballistic impact of woven fabrics, including mechanisms that affect ballistic performance, and well cited theoretical and experimental work conducted.

Research into the ballistic impact of woven fabrics rapidly grew after the introduction of high-modulus and high-strength yarns in the 1960s. Initial work was primarily experimental in nature and then took on an empirical approach. With the advent of high-speed computing, finite element techniques, and development of advanced commercial codes, coupled with advancements in photography, microscopy, measurement, and material testing systems, the nature of research evolved to include more accurate numerical, micromechanical, and multiscale constitutive techniques that were capable of capturing complex phenomena associated with the ballistic impact of fabrics.

It is apparent that a considerable amount of work still needs to be done before the exact mechanics of fabric ballistic impact can be understood and be replicated, especially interyarn, interply, and interfiber interactions and frictional effects. Approaches that utilize shell elements to model the fabric are computationally efficient and reasonably accurate, but cannot adequately capture phenomena, such as yarn pullout, yarn failure, and interyarn frictional effects. These effects can be captured by explicitly modeling each yarn with solid elements; however, this approach is limited by today's available computing power. Thus, there is some tradeoff in every approach in terms of accuracy and the complex phenomena that it can capture. In spite of this, each approach is usually able to represent the ballistic impact of fabrics with acceptable accuracy.

It is important to note that almost all of the parameters that affect the ballistic penetration resistance of a fabric are inter-related; thus studies that attempt to single out an individual effect cannot yield conclusive results unless all of the other parameters are explicitly presented, and then various combinations of these parameters are incorporated into the study before a fixed rule can be ascertained. Unfortunately, this makes the study very complicated.

Cheeseman and Bogetti [7] observed that there is research being conducted, which is propriety work, and therefore does not appear in open literature. This may lead to certain significant advances and concepts being missed by academic researchers who lean more toward technical journals as sources.

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